CLAIMS

What is claimed is:

1. A method of determining characteristics of an anisotropic earth formation, the method comprising:

transmitting acoustic energy into the earth formation, and wherein the earth formation breaks the acoustic energy into a fast polarization shear wave and a slow polarization shear wave;

receiving composite waveforms comprising components of both the fast and slow polarization shear waves;

decomposing the composite waveforms into decomposed waveforms;

estimating source waveforms from the decomposed waveforms to create estimated source waveforms; and

comparing the estimated source waveforms to determine characteristics of the anisotropic earth formation.

2. The method of determining characteristics of an anisotropic earth formation as defined in claim 1 wherein transmitting acoustic energy into the earth formation further comprises:

firing a first dipole transmitter in a first axial direction; then

firing a second dipole transmitter in an axial direction substantially azimuthaly perpendicular to the first axial direction.

3. The method of determining characteristics of an anisotropic earth formation as defined in claim 2 wherein receiving composite waveforms comprising components of both the fast and slow polarization shear waves further comprises:

receiving a first set of composite waveforms with a first dipole receiver pair associated with the firing of the first dipole transmitter;

receiving a second set of composite waveforms with a second dipole receiver pair associated with the firing of the first dipole transmitter;

receiving a third set of composite waveforms with the first dipole receiver pair associated with the firing of the second dipole transmitter; and

receiving a fourth set of composite waveforms with the second dipole receiver pair associated with the firing of the second dipole transmitter.

4. The method of determining characteristics of an anisotropic earth formation as defined in claim 3 wherein decomposing the composite waveforms into decomposed waveforms further comprises:

estimating a transfer function of the anisotropic earth formation comprising at least a strike angle for the anisotropy and an acoustic velocity;

decomposing the first and third set of composite waveforms using the strike angle to create a first decomposed waveform;

decomposing the second and fourth composite waveforms to create a second decomposed waveform; and

applying the inverse of the estimated transfer function to the decomposed waveforms to create the estimated source waveforms.

5. The method of determining characteristics of an anisotropic earth formation as defined in claim 1 wherein comparing the estimated source waveforms to determine the characteristic of the anisotropic earth formation further comprises:

calculating an objective function based on the estimated source waveforms; and

determining the characteristic of the anistropic earth formation based on a plot containing the objective function.

6. The method of determining characteristics of an anisotropic earth formation as defined in claim 5 wherein calculating an objective function based on the estimated source waveforms further comprises:

averaging the estimated source waveforms to determine an average estimated source waveform; and

determining a variance value of the estimated source waveforms using the average estimated source waveform, the variance value being the objective function.

7. The method of determining characteristics of an anisotropic earth formation as defined in claim 6 wherein averaging the estimated source waveforms to determine an average estimated source waveform further comprises determining the average estimated source waveform using substantially the following equation:

$$S_{EST_{AVG}}(t) = \frac{1}{N}\sum_{i=1}^{N} S_{EST_i}(t)$$

where $S_{EST_{AVG}}$ is the average estimated source waveform, N is the number of decomposed waveforms used to create the average estimated source signal, S_{EST_i} is the estimated source waveform for each decomposed waveform, and t is time.

8. The method of determining characteristics of an anisotropic earth formation as defined in claim 6 wherein determining a variance value of the estimated source waveforms using the average estimated source waveform further comprises:

$$\delta^2 = \sum_{i=1}^{N}(S_{EST_i}(t) - S_{EST_{AVG}}(t))^2$$

where δ^2 is the variance, $S_{EST_{AVG}}$ is the average estimated source waveform, N is the number of decomposed waveforms used to create the average estimated source signal, S_{EST_i} is the estimated source waveform for each decomposed waveform, and t is time.

9. The method of determining characteristics of an anisotropic earth formation as defined in claim 6 further comprising:

plotting multiple variance values calculated for multiple sets of estimated source waveforms; and

determining inflection points of the variance values within the plot as indicative of acoustic velocity within the earth formation.

10. The method of determining characteristics of an anisotropic earth formation as defined in claim 9 wherein comparing the estimated source waveforms to determine the acoustic velocity further comprises finding locations where the inflection points are minimas.

11. The method of determining characteristics of an anisotropic earth formation as defined in claim 10 further comprising estimating an error in the determination of the characteristic of the anisotropic earth formation based on a value of the objective function at the minimas.

12. The method of determining characteristics of an anisotropic earth formation as defined in claim 10 further comprising estimating an error in the determination of the characteristic of the anisotropic earth formation based on a curvature of the plot of the value of the objective function at the minimas.

13. The method of determining characteristics of an anisotropic earth formation as defined in claim 1 wherein comparing the estimated source waveforms to determine the acoustic velocity further comprises:

calculating a differences between each estimated source waveforms to obtain an objective function using substantially the following equation

$$\zeta = \sum_{i=1}^{N-1}(S_{EST_{i+1}} - S_{EST_i})^2$$

where ζ is the objective function, and N is the number of decomposed waveforms, and S_{EST_i} is the estimated source waveform for each decomposed waveform.

14. The method of determining characteristics of an anisotropic earth formation as defined in claim 13 wherein comparing the estimated source waveforms to determine the acoustic velocity further comprises:

plotting multiple values of the objective function calculated for multiple sets of estimated source waveforms; and

determining inflection points of the values of the objective function within the plot as indicative of acoustic velocity within the earth formation.

15. The method of determining characteristics of an anisotropic earth formation as defined in claim 14 wherein comparing the estimated source waveforms to determine the acoustic velocity further comprises finding locations where the inflection points are minimas.

16. The method of determining characteristics of an anisotropic earth formation as defined in claim 15 wherein an error in the determination of the acoustic velocity is proportional to the a curvature of the values of the objective function at the minimas.

17. The method of determining characteristics of an anisotropic earth formation as defined in claim 1 wherein comparing the estimated source waveforms to determine characteristics of the anisotropic earth formation further comprises comparing the estimated source waveforms to determine at least one of the fast and slow polarization shear wave acoustic velocities.

18. The method of determining characteristics of an anisotropic earth formation as defined in claim 1 wherein comparing the estimated source waveforms to determine characteristics of the anisotropic earth formation further comprises comparing the estimated source waveforms to determine a strike angle of the anisotropy.

19. The method of determining characteristics of an anisotropic earth formation as defined in claim 18 further comprising determining an error estimate of the strike angle by comparing an angle between the fast and slow polarization shear waves.

20. In a system with a logging tool having a dipole transmitter pair and a plurality of dipole receiver pairs spaced apart from the dipole transmitter pair and from each other, and where the orientation of each dipole transmitter is known, and where each of the plurality of dipole receiver pairs has one dipole receiver axially parallel with one of the dipole transmitters and another dipole receiver axially parallel with another of the dipole transmitters, a method of determining a velocity of a fast and slow shear wave polarizations in an anisotropic earth formation comprising:

transmitting acoustic signals with the dipole transmitters;

receiving the acoustic signals as composite signals with the plurality of dipole receiver pairs;

decomposing the composite signals into a plurality of decomposed signals;

estimating a source signal for each of the plurality of decomposed signals to create a plurality of estimated source signals; and

determining the acoustic velocity of the fast and slow polarized shear waves by comparison of the plurality of estimated source signals.

21. The method of determining a velocity of fast and slow shear wave polarizations as defined in claim 20 wherein transmitting an acoustic signal with the dipole transmitters further comprises, at each depth level of interest:

firing a first dipole transmitter of the dipole transmitter pair; and then

firing a second dipole transmitter of the dipole transmitter pair.

22. The method of determining a velocity of fast and slow shear wave polarizations as defined in claim 20 wherein decomposing the composite signals into a plurality of decomposed signals further comprises:

decomposing the composite signals a plurality of times using a plurality of strike angles in a range of possible strike angle extending from -90^0 to $+90^0$; and for each of the plurality of strike angles

estimating a source signal for each of the plurality of decomposed signals to create a plurality of estimated source signals.

23. The method of determining a velocity of fast and slow shear wave polarizations as defined in claim 22 wherein decomposing the composite received signals a plurality of times using a plurality of strike angles in a range of possible strike angles extending from -90^0 to $+90^0$ further comprises determining, for each strike angle in the range of possible strike angles, decomposing the composite received signals using substantially the following equation:

$$DS\ (t) = \cos^2(\theta)\, R_{XX}(t) + \sin(\theta)\cos(\theta)\, [R_{XY}(t)+R_{YX}(t)] + \sin^2(\theta)\, R_{YY}(t)$$

where DS(t) is the decomposed signal, θ is the strike angle, R_{XX} is a composite signal received by a receiver oriented in the X direction upon firing of a transmitter in the X direction, R_{YX} is the composite signal received by a receiver oriented in the Y direction upon firing of the transmitter in the X direction, R_{YY} is a composite signal receiver by a receiver oriented in the Y direction upon firing of the transmitter in the X direction, and R_{XY} is a composite signal received by a receiver oriented in the X direction upon firing of the transmitter in the Y direction.

24. The method of determining a velocity of fast and slow shear wave polarizations as defined in claim 20 wherein decomposing the composite signals into a plurality of decomposed signals further comprises:

determining a strike angle of the earth formation; and

decomposing the plurality of composite signals using the strike angle determined.

25. The method of determining a velocity of fast and slow shear wave polarizations as defined in claim 24 wherein determining the strike angle of the earth formation further comprises solving the following equation for the strike angle θ:

$$\sin(2\theta)[R_{XX}(t) - R_{YY}(t)] - \cos(2\theta)\,[R_{XY}(t) + R_{YX}(t)] = 0$$

where R_{XX} is a composite signal received by a receiver oriented in the X direction upon firing of a transmitter in the X direction, R_{YX} is the composite signal received by a receiver oriented in the Y direction upon firing of the transmitter in the X direction, R_{YY} is a composite signal received by a receiver oriented in the Y direction upon firing of the transmitter in the X direction; and R_{XY} is a composite signal received by a receiver oriented in the X direction upon firing of the transmitter in the Y direction.

26. The method of determining a velocity of fast and slow shear wave polarizations as defined in claim 25 wherein decomposing the plurality of composite signals using the strike angle determined further comprises determining the fast polarization time series, FP(t) and the slow polarization time series SP(t) with substantially the following equations:

$$FP(t)=\cos^2(\theta)\,R_{XX}(t) + \sin(\theta)\cos(\theta)\,[R_{XY}(t)+R_{YX}(t)] + \sin^2(\theta)\,R_{YY}(t)$$

$$SP(t) = \sin^2(\theta)\, R_{XX}(t) - \cos(\theta)\sin(\theta)\, [R_{XY}(t) + R_{YX}(t)] + \cos^2(\theta)\, R_{YY}(t).$$

27. The method of determining a velocity of fast and slow shear wave polarizations as defined in claim 20 wherein decomposing the composite received signals and estimating a source signal for each of the plurality of decomposed signals to create a plurality of estimated source signals further comprises:

estimating a transfer function of the formation comprising at least a strike angle of the anisotropy and a slowness of acoustic waves within the formation;

decomposing the composite received signals based on the assumed strike angle; and

calculating the estimated source signals by applying the transfer function to each of the decomposed signals.

28. The method of determining a velocity of fast and slow shear wave polarizations as defined in claim 20 further comprising performing the transmitting and receiving steps using a wireline formation tester.

29. The method of determining a velocity of fast and slow shear wave polarizations as defined in claim 20 further comprising performing the transmitting and receiving steps with a tool on a drill string during a drilling process.

30. In an anisotropic earth formation where an induced shear wave breaks up into a fast polarization component and a slow polarization component, a method of determining characteristics of the earth formation comprising:

a) generating acoustic signals with dipole transmitter pair by firing a first dipole transmitter, then firing a second dipole transmitter;

b) receiving at a first dipole receiver pair acoustic energy composite signals containing information about both the fast and slow polarization components;

c) receiving at a second dipole receiver pair acoustic energy composite signals containing information about both the fast and slow polarization components;

d) decomposing the signals of the first dipole receiver pair into a first decomposed signal for a strike angle;

e) decomposing the signals of the second dipole receiver pair into a second decomposed signal for the strike angle;

f) estimating a an assumed slowness of the earth formation;

g) estimating a first source wavelet based on the first decomposed signal;

h) estimating a second source wavelet based on the second decomposed signal;

i) comparing the first and second source wavelets to obtain an objective function;

j) plotting the objecting function as a function of slowness of the assumed transfer function, a start time within the decomposed signals, and strike angle;

k) repeating steps f) through j) for a plurality of assumed transfer functions;

l) repeating steps f) through k) for a plurality of start times within the decomposed signal; and

m) repeating steps d) through l) for a plurality of strike angles.

31. The method of determining characteristics of an earth formation as defined in claim 30 wherein decomposing the signals of the first dipole receiver pair into a first decomposed signal

further comprises calculating the first decomposed signal using substantially the following equation:

$$DS(t) = \cos^2(\theta)\, R_{XX}(t) + \sin(\theta)\cos(\theta)\, [R_{XY}(t)+R_{YX}(t)] + \sin^2(\theta)\, R_{YY}(t)$$

where DS(t) is the decomposed signal, θ is the strike angle, R_{XX} is a signal received by a first receiver of the first receiver pair with an axis oriented in an X direction when a transmitter in the X direction is fired, R_{XY} is a signal received by the first receiver of the first receiver pair when a transmitter in a transmitter in the Y direction is fired, R_{YX} is a signal received by a second receiver of the first receiver pair with an axis oriented in the Y direction when the transmitter oriented in the X direction is fired, and R_{YY} is a signal received by the second receiver oriented in the Y direction when the transmitter oriented in the Y direction is fired.

32. The method of determining characteristics of an earth formation as defined in claim 30 wherein decomposing the signals of the second dipole receiver pair into a second decomposed signal further comprises calculating the first decomposed signal using substantially the following equation:

$$DS(t) = \cos^2(\theta)\, R_{XX}(t) + \sin(\theta)\cos(\theta)\, [R_{XY}(t)+R_{YX}(t)] + \sin^2(\theta)\, R_{YY}(t)$$

where DS(t) is the decomposed signal, θ is the strike angle, R_{XX} is a signal received by a first receiver of the second receiver pair with an axis oriented in an X direction when a transmitter in the X direction is fired, R_{XY} is a signal received by the first receiver of the second receiver pair when a transmitter in a transmitter in the Y direction is fired, R_{YX} is a signal received by a second receiver of the second receiver pair with an axis oriented in the Y direction when the transmitter oriented in the X direction is fired, and R_{YY} is a signal received by the second receiver oriented in the Y direction when the transmitter oriented in the Y direction is fired.

33. The method of determining a characteristic of an earth formation as defined in claim 30 wherein comparing the first and second source wavelets to obtain an objective function further comprises:

calculating an average estimated source wavelet; and

calculating a variance of the estimated source wavelets from the average estimated source wavelet.

34. The method of determining a characteristic of an earth formation as defined in claim 33 wherein calculating the average estimated source wavelet further comprises calculating the average estimated source wavelet using substantially the following equation:

$$S_{EST_{AVG}}(t) = \frac{1}{N}\sum_{i=1}^{N} S_{EST_i}(t)$$

where $S_{EST_{AVG}}$ is the average estimated source signal, N is the number estimated source wavelets, S_{EST_i} is the estimated source wavelet, and t is time.

35. The method of determining a characteristic of an earth formation as defined in claim 34 wherein calculating a variance of the estimated source wavelets from the average estimated source wavelet further comprises calculating the variance using substantially the following equation:

$$\delta^2 = \sum_{i=1}^{N} (S_{EST_i}(t) - S_{EST_{AVG}}(t))^2$$

where δ^2 is the variance.

36. The method of determining a characteristic of an earth formation as defined in claim 30 wherein comparing the first and second source wavelets to obtain an objective function further comprises determining a difference between the estimated source wavelets as the objective function.

37. The method of determining a characteristic of an earth formation as defined in claim 36 wherein determining a difference between the estimated source wavelets further comprises calculating an objective function using substantially the following equation:

$$\zeta = \sum_{i=1}^{N-1} (S_{EST_{i+1}} - S_{EST_i})^2$$

where ζ is the objective function, S_{EST_i} is the estimated source wavelet, and N is the number of estimated source wavelets.

38. A method of determining an orientation of fast and slow polarized shear waves in an anisotropic earth formation, the method comprising:

transmitting acoustic energy into the earth formation, and wherein the earth formation breaks the acoustic energy into the fast polarization shear wave and the slow polarization shear wave;

receiving composite waveforms comprising components of both the fast and slow polarization shear waves;

decomposing the composite waveforms into decomposed waveforms;

estimating source waveforms from the decomposed waveforms to create estimated source waveforms; and

comparing the estimated source waveforms to determine the orientation of fast and slow polarized shear waves.

39. The method of determining an orientation of fast and slow polarized shear waves in an anisotropic earth formation as defined in claim 38 wherein transmitting acoustic energy into the earth formation further comprises:

firing a first dipole transmitter in a first axial direction; then

firing a second dipole transmitter in an axial direction substantially azimuthaly perpendicular to the first axial direction.

40. The method of determining an orientation of fast and slow polarized shear waves in an anisotropic earth formation as defined in claim 39 wherein receiving composite waveforms comprising components of both the fast and slow polarization shear waves further comprises:

receiving a first set of composite waveforms with a first dipole receiver pair associated with the firing of the first dipole transmitter;

receiving a second set of composite waveforms with a second dipole receiver pair associated with the firing of the first dipole transmitter;

receiving a third set of composite waveforms with the first dipole receiver pair associated with the firing of the second dipole transmitter; and

receiving a fourth set of composite waveforms with the second dipole receiver pair associated with the firing of the second dipole transmitter.

41. The method of determining an orientation of fast and slow polarized shear waves in an anisotropic earth formation as defined in claim 40 wherein decomposing the composite waveforms into decomposed waveforms further comprises:

decomposing the first and third set of composite waveforms to create a first decomposed waveform; and

decomposing the second and fourth composite waveforms to create a second decomposed waveform.

42. The method of determining an orientation of fast and slow polarized shear waves in an anisotropic earth formation as defined in claim 38 wherein estimating source waveforms from the decomposed waveforms to create estimated source waveforms further comprises:

estimated acoustic velocity of the earth formation; and

applying the estimated acoustic velocity to the decomposed waveforms to create the estimated source waveforms.

43. The method of determining an orientation of fast and slow polarized shear waves in an anisotropic earth formation as defined in claim 38 wherein comparing the estimated source waveforms to determine the orientation of fast and slow polarized shear waves further comprises:

calculating an objective function based on the estimated source waveforms;

plotting the values of the objective function to create a plot; and

determining the orientation of fast and slow polarized shear waves by a search for inflection points in a plot containing the objective function.

44. The method of determining an orientation of fast and slow polarized shear waves in an anisotropic earth formation as defined in claim 43 further comprising:

plotting multiple objective function values calculated for multiple sets of estimated source waveforms; and

determining inflection points of the objective function values within the plot as indicative of orientation of fast and slow polarized shear waves within the earth formation.

45. The method of determining an orientation of fast and slow polarized shear waves in an anisotropic earth formation as defined in claim 44 wherein comparing the estimated source waveforms to determine the acoustic velocity further comprises finding locations where the inflection points are minimas.

46. The method of determining an orientation of fast and slow polarized shear waves in an anisotropic earth formation as defined in claim 45 further comprising estimating an error in the determination of the orientation of fast and slow polarized shear waves based on a curvature of the value of the objective function at the minimas.

47. The method of determining an orientation of fast and slow polarized shear waves in an anisotropic earth formation as defined in claim 43 wherein calculating an objective function based on the estimated source waveforms further comprises:

averaging the estimated source waveforms to determine an average estimated source waveform; and

determining a variance value of the estimated source waveforms using the average estimated source waveform, the variance value being the objective function.

48. The method of determining an orientation of fast and slow polarized shear waves in an anisotropic earth formation as defined in claim 47 wherein averaging the estimated source waveforms to determine an average estimated source waveform further comprises determining the average estimated source waveform using substantially the following equation:

$$S_{EST_{AVG}}(t) = \frac{1}{N}\sum_{i=1}^{N} S_{EST_i}(t)$$

where $S_{EST_{AVG}}$ is the average estimated source waveform, N is the number of decomposed waveforms used to create the average estimated source signal, S_{EST_i} is the estimated source waveform for each decomposed waveform, and t is time.

49. The method of determining an orientation of fast and slow polarized shear waves in an anisotropic earth formation as defined in claim 47 wherein determining a variance value of the estimated source waveforms using the average estimated source waveform further comprises:

$$\delta^2 = \sum_{i=1}^{N}(S_{EST_i}(t) - S_{EST_{AVG}}(t))^2$$

where δ^2 is the variance, $S_{EST_{AVG}}$ is the average estimated source waveform, N is the number of decomposed waveforms used to create the average estimated source signal, S_{EST_i} is the estimated source waveform for each decomposed waveform, and t is time.

50. The method of determining an orientation of fast and slow polarized shear waves in an anisotropic earth formation as defined in claim 47 further comprising:

plotting multiple variance values calculated for multiple sets of estimated source waveforms; and

determining inflection points of the variance values within the plot as indicative of velocity of fast and slow polarized shear waves within the earth formation.

51. The method of determining an orientation of fast and slow polarized shear waves in an anisotropic earth formation as defined in claim 50 wherein comparing the estimated source waveforms to determine the acoustic velocity further comprises finding locations where the inflection points are minimas.

52. The method of determining an orientation of fast and slow polarized shear waves in an anisotropic earth formation as defined in claim 38 wherein comparing the estimated source waveforms to determine the orientation further comprises:

calculating a differences between each estimated source waveforms to obtain an objective function using substantially the following equation

$$\zeta = \sum_{i=1}^{N-1} (S_{EST_{i+1}} - S_{EST_i})^2$$

where ζ is the objective function, and N is the number of decomposed waveforms, and S_{EST_i} is the estimated source waveform for each decomposed waveform.

53. The method of determining an orientation of fast and slow polarized shear waves in an anisotropic earth formation as defined in claim 52 wherein comparing the estimated source waveforms to determine the acoustic velocity further comprises:

plotting multiple values of the objective function calculated for multiple sets of estimated source waveforms; and

determining inflection points of the values of the objective function within the plot as indicative of orientation of fast and slow polarized shear waves within the earth formation.

54. The method of determining an orientation of fast and slow polarized shear waves in an anisotropic earth formation as defined in claim 53 wherein comparing the estimated source waveforms to determine the acoustic velocity of fast and slow polarized shear waves further comprises finding locations where the inflection points are minimas.

55. The method of determining an orientation of fast and slow polarized shear waves in an anisotropic earth formation as defined in claim 38 further comprising performing the transmitting and receiving steps using a wireline formation tester.

56. The method of determining an orientation of fast and slow polarized shear waves in an anisotropic earth formation as defined in claim 38 further comprising performing the transmitting and receiving steps with a tool on a drill string during a drilling process.

57. The method of determining an orientation of fast and slow polarized shear waves in an anisotropic earth formation as defined in claim 38 further comprising comparing the estimated source waveforms to determine the acoustic velocity of the fast and slow polarized shear waves.